ANALYSIS OF A METHOD FOR PRECISELY RELATING A SEAFLOOR POINT TO A DISTANT POINT ON LAND

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ABSTRACT

This report describes a study of the environmental constraints and engineering aspects of the acoustic portion of a system for making geodetic ties between undersea reference points and others on land.

Important areas in which to make such observations initially would be from the California mainland out to oceanic points seaward of the San Andreas fault, and across the Aleutian Trench The overall approach would be to operate a GPS receiver in a relative positioning (interferometric) mode to provide the long range element of the baseline determination (10 to 1,000 km) and an array of precision sea floor acousitc transponders to link the locally moving sea surface GPS antenna location to a fixed sea floor point

Analyses of various environmental constraints (tides, waves, currents, sound velocity variations) lead to the conclusion that, if one uses a properly designed transponder having a remotely controllable precise retransmission time delay, and is careful with regard to methods for installing these on the sea floor, one should, in many ocean locations, be able to achieve sub-decimeter overall system accuracy. Achievement of cm accuracy or better will require additional understanding of time and space scales of variation of sound velocity structure in the ocean at relevant locations

Logical next steps would be construction and testing of a prototype transponder, conduct of precise sound velocity measurements at selected locations and development of necessary data reduction algorithms for fitting the GPS to the acoustic observations. Following these it should be possible to make a field demonstration of the acoustic portion of the system independently and finally to integrate the GPS portion and begin to carry out the desired geodetic measurement programs

1 Carpentier, M. H., *Radars,* pp 75-78, Gordon and Breach, New York, NY, 1968.

2. Desaubies, Y., Fluctuatıons of sound propagatıng vertıcally through the ocean, *JASA, 74,* 1245-1249, 1983

3. Fisher, F H and F N. Spıess, FLIP - Floating Instrument Platform, *J. Acoust. Soc. Am., 35,* 1633-1644, 1963.

4. Garrett, C. and Munk,W H., Space time scales of ınternal waves: A progress report, *J Geophys Res., 80,* 291-297, 1975.

5. Panel on Crustal Movement Measurements, Committee on Geodesy, and Commıttee on Seısmology, National Research Councıl, Geodetic Monıtoring of Tectonıc Deformatıon - Toward a Strategy, *National Academy Prss,* Washington, DC, 1981.

6. Panel on Ocean Bottom Posıtionıng, Commıttee on Geodesy, Seafloor Referenced Posıtıonıng - Needs and Opportunities, *Natıonal Academy Press,* Washington, DC, 1983

7. Porter, R. R., Spindel, R C., and Jaffee, R. J , CW beacon system for hydrophone motıon determınatıon, *J. Acoust. Soc of Amer., 53,* 1691-1698, 1973

8. Rudnıck, P, Motion of a large spar buoy in sea waves, *J. Shıp Res., 11,* 257-267, 1967

9. Spiess, F N , C D Lowenstein, D E. Boegeman, and F V Pavlıcek, Precision transponder and method for communıcatıon therewıth, U S. Patent 4,214,314, 1980

10. Spiess, F. N , Acoustic technıques for marıne geodesy, *Marine Geodesy, 3,* 13-27, Crane, Russak & Co , Inc., New York, 1979

11 Spiess, F. N , Analysıs of a possible sea floor strain measurement, *Marıne Geodesy,* ın press

1. Introduction

Given the large fraction of the earth's crust which is covered by the world's oceans and the fact that most major plate boundaries are under water, the ability to measure strain accumulation between widely separated points on the sea floor and others on land could play an important role in understanding and predicting tectonic activity of many types. This was recognized by the Panel on Crustal Movement Measurements of the National Research Council (1981) which included among its conclusions: "We recommend development of a capability to measure, to a 10 cm accuracy, motions of points on the ocean floor up to several hundred kilometers offshore with respect to reference points on land." Both their report and that of the NRC Panel on Ocean Bottom Positioning (1983) recognized that this would require a "ship" as an intermediate point, positioned relative to a distant point by using signals from Global Positioning System (GPS) satellites and using underwater acoustics to make the tie from the ship to a local sea floor reference system. This report examines in detail work done under NASA grant NAG5-320 to delineate the problems and possibilities of making the acoustic tie successfully, involving only modest extensions beyond today's ocean technology capabilities

We will present a brief account of the approach, followed by a discussion of the environmental constraints which dictate system design and auxiliary measurement requirements, an outline of the necessary system emphasizing the underwater acoustic portion, and finally a description of a method for validating the performance of the sonar portion prior to implementing other (e g , GPS) aspects of the system.

Before launching into the above topics, however, it is appropriate to discuss a few of the geodynamic problems to which this system would be relevant.

Various studies (Airlie House, 1983) have pointed out three classes of plate tectonic questions in which description of crustal motion or deformation is important The first of these is the gross relative motion among the plates themselves, second is deformation of the interiors of plates and third is the nature of strain build-up in the vicinity of plate boundaries -- transform faults, spreading centers and subduction zones. In every one of these problems measurements including oceanic sites could make substantial contributions

With regard to gross interplate motion one immediately recognizes that two of the major plates (Pacific and Nazca) as well as most of the identified smaller ones (Cocos, Juan de Fuca, etc.) are almost completely oceanic. Measurement of motion of the Nazca and Pacific plates relative to others has been attacked by establishing laser ranging and/or VLBI stations on islands. These features quite probably, in the long run, track the motion of the plates on which they ride and provide sites which can easily be operational more or less continuously It is possible, however, that in the short term (few-years) their motion relative to their parent plates -- elevation changes and tilting -- could introduce "noise" at the observation sites which would obscure or confuse the results. It would thus be reassuring to be able at relevant intervals to be able to relate these island sites to sea floor points more typical of the normal crust of the plates involved This was discussed at the Airlie House 1983 Geodynamics Program meeting. At that time the most logical initial location on which to focus was the Hawaiian Islands where, at distances of a few hundred km, the sea floor and overlying ocean (as well as operational convenience) would be particularly amenable to carrying out measurements of this sort

The smaller plates (e g., Juan de Fuca, Cocos) generally do not offer convenient island sites. Determination of their gross displacement may not be particularly important, since they are captured by the surrounding larger plates. There is, however, evidence that they may rotate significantly because of the manner in which they accommodate to the underlying driving forces and the adjacent larger plates. Determination of the motion of several points on these features relative to island and continental sites on the major plates could thus provide insight into this aspect of plate tectonics.

Intra-plate deformation is an important problem being addressed by direct measurement on land in North America. A major part of the North American plate however, lies between the continent and the Mid-Atlantic Ridge It would be particularly interesting to know whether substantial intra-plate deformation occurs between the oceanic and continental portions of this plate and whether there is more internal deformation taking place within one or the other of these disparate sections. Intra-plate deformation is also a major problem within the Pacific and Nazca plates Particularly in the Nazca case the number of available island sites is inadequate to address this question

The most exciting zones for geodetic measurement of deformation are those associated with plate

boundaries In the present context the most interesting (and important from the applied, earthquake prediction view) are those boundaries in which the continents are involved. These bring one immediately to focus on transform faults and subduction zones and to specialize to a pair of features of great importance to the United States -- the San Andreas fault area and the Aleutian Trench

The most intensively studied tectonically active zone is the San Andreas Its immediate vicinity is accessible and has been the scene of application of almost every available technique. Points are also available on the continental side to allow one to track the pattern of strain accumulation as it is distributed into the less disturbed adjacent areas. Unfortunately, on the Pacific side of the fault zone the only above-water points are on the Channel Islands and near Point Concepcion. While these can provide interesting insight there is considerable question, since they ride on crust substantially dissimilar to that of the bulk of the Pacific Plate, as to whether they represent the true motion of that entity. In fact, a very important question is whether significant deformation is taking place today in that Borderland region Establishment of a few points on the nearby deep ocean floor would be both operationally feasible and scientifically rewarding.

The second plate interaction problem of interest is also related to the basics of plate tectonics and the immediate question of understanding (predicting?) earthquakes in an important region. This is the monitoring of strain build-up across the Aleutian Trench. In the most interesting portions of that zone no islands are available as nearby base points on the oceanic side. This, combined with the nature of the processes involved, makes this the most attractive region from the scientific point of view for initiating a program of observation of changes of baseline lengths over distances of a few hundred km, with one set of reference points on land and the other set on the sea floor.

2. *Basic Concept*

Given the depths involved (a km or more) the only feasible measurement approaches are those based on transmission of sound through the water. The primary difficulty with this is that, particularly in the upper part of the water column, the effective sound velocity may change on an hourly basis by several parts in 10^5 which can translate into errors of tens of centimeters. This would not be an obstacle if the sound velocity could be measured quickly over the entire water column; however, the only

methods available even in principle require cycling an instrument up and down through the water column Bender (Panel on Crustal Movement Measurements, 1981), with this in mind, noted the advantage of working " over the center of the baseline between two transponders" using travel time difference measurements, as a means of minimizing dependence on knowledge of sound propagation speed. This lead to the idea of placing a trio of acoustic units (controlled transmitters, receivers or transponders) firmly on the sea floor and working at the sea surface near the point above the center of the array. It is then intuitively clear that only a crude value of the sound speed is needed – at the exact center of the array one can know one's position without knowing the sound speed at all.

If the acoustic units are located at depths z_i and horizontal coordinates x_i, y_i, and if the sea surface point being tracked simultaneously by the GPS (or laser ranging or VLBI) and by the acoustic system is at x,y, and 0 then the acoustic travel times (with sound velocity c) would be:

$$ct_i = [(x_i - x)^2 + (y_i - y)^2 + z_i^2]^{1/2}$$

The time differences $T_{ij} = t_i - t_j$ would then be:

$$cT_{ij} = [(x_i - x)^2 + (y_i - y)^2 + z_i^2]^{1/2} - [(x_j - x)^2 + (y_j - y)^2 + z_j^2]^{1/2}$$

We then choose to operate at the surface, close to the origin, where the origin is defined by:

$$x = y = 0 \ at \ T_{ij} = 0 \text{ for } all \ i \text{ and } j$$

This means·

$$r_0^2 = x_i^2 + y_i^2 + z_i^2 \text{ for } all \ i \ (1,2,3).$$

Using element number one as the primary reference unit:

$$cT_{1j} = [r_0^2 - 2(xx_1 + yy_1) + x^2 + y^2]^{1/2} - [r_0^2 - 2(xx_j + yy_j) + x^2 + y^2]^{1/2}$$

Operation close to the origin is defined by x and $y \ll r_0$. We are also free to orient the coordinate system and thus choose this such that $y_1 = 0$. Then

$$\frac{cT_{1j}}{r_0} = [1 - \frac{2xx_1}{r_0^2} + \frac{x^2+y^2}{r_0^2}]^{1/2} - [1 - \frac{2(xx_j + yy_j)}{r_0^2} + \frac{x^2+y^2}{r_0^2}]^{1/2}$$

In the extreme of small x and y relative to r_0 we have:

$$\frac{cT_{1j}}{r_0} = \frac{x(x_j - x_1) + yy_j}{r_0^2}$$

Solving the pair of equations for $j = 2$ and 3, gives

$$x = \frac{cr_0(y_3T_{12}-y_2T_{13})}{(x_2-x_1)y_3-(x_3-x_1)y_2} \; ; \; y = \frac{cr_0[(x_3-x_1)T_{12}-(x_2-x_1)T_{13}]}{(x_2-x_1)y_3-(x_3-x_1)y_2}$$

At this point the strength of the method becomes clear. The allowable error in c for a given error in x is:

$$\frac{E_c}{c} = \frac{E_x}{x}$$

Thus if one expects to be able to hold the surface observation point within 100 m of the origin and desires E_x to be one cm then the allowable uncertainty in c is a part in 10^4 which should be reasonably achievable in many parts of the ocean. If one is satisfied with 10 cm position uncertainty then one can either relax the requirement on c to a part in 10^3 (which could be achieved with simple near surface bathythermograph data plus a deep hydrocast) or one could expand the zone of operation to several hundred meters radius

This ideal situation is disturbed by the fact that it assumes that the sound velocity is identical on the acoustic paths to all three of the sea floor markers. At some level of accuracy this condition will not be met. This point will be discussed further in section 3 Meanwhile this simple formulation (which ignores second order terms in x/r_0) allows us to examine an important aspect of this system – the interaction between time difference measurement accuracy and the relative positions of the markers on the sea floor

The fact that water depths of the order of 5 km must be accommodated means that the acoustic paths must be at least that long. The frequency dependence of sound absorption and background noise, taken with the sound source levels which can be achieved with long lived battery powered sea floor packages leads eventually (as will be discussed below in section 4) to the conclusion that we can measure travel times to within 10 μsec. Taking a level sea floor for simplicity (depth $= z_o$) and recalling that·

$$r_o^2 = z_o^2+x_1^2 = z_o^2+x_2^2+y_2^2 = z_o^2+x_3^2+y_3^2$$

one can express the coordinates of the three markers in polar form with equal horizontal radii, $R^2=x_i^2+y_i^2$ and angles θ_i ($\theta_1=0$). Then we have $x_i=R\cos\theta_i$ and $y_i=R\sin\theta_i$ and

$$x = \frac{cr_o}{R}\,\frac{T_{12}\sin\theta_3-T_{13}\sin\theta_2}{(\cos\theta_2-1)\sin\theta_3-(\cos\theta_3-1)\sin\theta_2}$$

$$y = \frac{cr_o}{R} \frac{[(\cos\theta_3-1)T_{12}-(\cos\theta_2-1)T_{13}]}{(\cos\theta_2-1)\sin\theta_3-(\cos\theta_3-1)\sin\theta_2}$$

For simplicity we choose an isosceles triangle configuration, putting $\sin\theta = \sin\theta_3 = -\sin\theta_2$ and $\cos\theta = \cos\theta_2 = \cos\theta_3$ and

$$x = \frac{cr_o(T_{12}+T_{13})}{2R(\cos\theta-1)} \; ; \; y = \frac{cr_o(T_{12}-T_{13})}{2R\sin\theta} = \frac{cr_o T_{32}}{2R\sin\theta}$$

or

$$x = \frac{cr_o(t_2+t_3-2t_1)}{2R(\cos\theta-1)} \; ; \; y = \frac{cr_o(t_3-t_2)}{2R\sin\theta}$$

If errors in t_i are independent and Gaussian then

$$E_x^2 = \frac{3(cr_o)^2}{2R^2(\cos\theta-1)^2} E_t^2 \text{ and } E_y^2 = \frac{(cr_o)^2}{2\ R^2\sin^2\theta} E_t^2$$

At $\theta=0$, E_x and E_y both become infinite (since all three units are at one point) while at $\theta=\pi$ (all units on the x axis) E_y is infinite The two errors are equal at $\theta=120\,^\circ$, and at that point:

$$E_x = E_y = \sqrt{\frac{2}{3}} \frac{cr_o}{R} E_t$$

Figure 1 shows a plot of $E_x=E_y$ for a range of values of R and water depths of 2 and 5 km. Basic system design (section 4) must be pointed toward the deep water case, with increasing range demanding increased transponder power. A range about 7 km thus appears to be a reasonable compromise, corresponding to a configuration radius of about 5 km for the deep water case. The array configuration can, of course, be adjusted depending on water depth.

Matching of the acoustic navigation net to the interferometrically determined GPS coordinates would be carried out in much the same manner as we now match our transponder navigated surveys to the present satellite navigation system A large number of pairs of positions measured simultaneously with both systems are simply fitted to each other by a least squares adjustment.

While this approach requires some ingenuity to be realized in practice (because of environmental aspects to be discussed in section 3) it does appear that individual measurement accuracies of a few cm are achievable and that with reasonable times on station the overall uncertainty of the sea floor marker system origin's positioning in GPS coordinates can be reduced to the order of one to ten centimeters given our present imperfect knowledge of the ocean. With improved understanding of spatial coherence

and temporal scales of hydrodynamic phenomena in the open sea (internal waves and turbulence) this situation can be better defined and appropriate measurement instants and averaging approaches can be selected to further reduce these uncertainties.

3. Environmental Constraints

Almost every aspect of the ocean environment enters this problem, influencing design choices and in the end limiting the ultimate achievable accuracy In most instances our knowledge of the nature of the particular environmental phenomenon is more than adequate for our purposes. The one exception is the difference between the integrated sound velocity structure on the several paths, although even in that instance enough is known to provide guidance for design and indication of feasibility at a useful level. The topics of concern are: currents, tides, waves, bottom topography, sound absorption, ambient noise and sound speed

The effects of ocean currents can best be examined by considering a simple case. Suppose a uniform ocean of depth z, sound speed c, and a uniform horizontal current of speed u If there are two fixed points, one at the sea surface (A) and one on the bottom (B) with horizontal separation L (L positive for downstream propagation). Then the travel time, t, is given by the equation.

$$c^2t^2 = z^2 + (L-ut)^2$$

which leads to:

$$t = \frac{c\sqrt{(z^2+L^2)(1-\frac{u^2}{c^2})+\frac{u^2}{c^2}L^2-uL}}{c^2-u^2}$$

If there were two transmitters separated a distance 2D on the sea floor, sending synchronized signals to a sea surface point directly above the midpoint between the transmitters, then, if all three points lie in a vertical plane containing the horizontal current vector the travel time difference between the two acoustic paths to the surface point would be:

$$T = \frac{2uD}{c^2-u^2}$$

This would be indistinguishable from the case of no current, but a small displacement, x, of the sea surface point from the mid-point amounting to

$$x = \frac{u}{c}\,(z^2+D^2)^{1/2}$$

If c = 1.5 km/sec and $(z^2+D^2)^{1/2} = 6$ km and it is desired to hold the error in x to 1 cm it would be necessary to know the current to 2.5 x 10^{-3} m/sec, which would be an unreasonable requirement. If, on the other hand one uses two-way transmission (the transponder approach) then the round trip travel time for any path would be:

$$t = \frac{2c\sqrt{(z^2+L^2)(1-\frac{u^2}{c^2})+\frac{u^2}{c^2}L^2}}{c^2-u^2}$$

and the travel time difference for the surface midpoint situation would be zero, just as for the still water case. For each acoustic path there would still be a fractional timing correction of:

$$K = \frac{u^2}{c^2}\,(1+\frac{L^2}{z^2+L^2})$$

In the deep ocean the currents averaged over the entire water column essentially never exceed one knot (0 5 m/sec), thus the correction term, for reasonable values of L and z, would be less than 2 x 10^{-7} and can be neglected.

It is thus clear that one is driven to the transponder approach even though that leads to further complexities due to wave driven motion of the near-surface point being tracked, as will be discussed below.

Before treating wave-related phenomena, however, we will discuss the simpler situation for the tides. These enter in three ways -- their direct effect on the vertical dimensions involved in relating the horizontal coordinates to the travel time differences, their effect on the sound propagation speed and their effect on the lengths of the baselines being measured from the sea surface location to some other site hundreds or thousands of km away.

Water depth enters the problem explicitly primarily through the quantity r_0 and in a secondary (negligible) manner through the dependence of sound velocity on pressure. Since the geometric quantities will be determined implicitly through the process of matching the acoustic positions with the GPS ones, we are only concerned with how these might vary due to causes unrelated to geodynamics. Tidal effects thus deserve prime consideration. Since the open ocean tidal range is very small compared with

the total water depth we can examine this effect by differentiating the expressions for x and y derived above for the equilateral triangle case. This leads us to:

$$E_x = \frac{xz_o}{R^2+z_o^2}\,E_z \text{ and } E_y = \frac{yz_o}{R^2+z_o^2}\,E_z$$

Taking $E_x = E_y = 10^{-2}$ m, $x = y = 10^2$ m and two pairs of values for R and z_0 (2 km for each and 5 km for each) leads to an allowable $E_z = 0.4$ m for the shallow case and $E_z = 1$ m for the deep one It thus appears that implementation of a sea floor pressure gauge capable of resolving differences in pressure with 0.2 m accuracy (existing quartz units can achieve this) will suffice. Since we are only concerned with knowing a pressure change of 2 m or less with 10% accuracy, we need not know the detailed characteristics of the water column. The correction would be inserted in the same manner as for the gross sound speed, which will be discussed in section 4.

Sound speed varies as a function of pressure, temperature and salinity and the average over the entire water column enters this problem. As the water depth increases or decreases, with the changing element having a sound speed somewhat different from the average, it will alter the average value slightly. The resulting effective change, being uniform over all the paths, will, however, be negligible.

There is a source of error introduced by a combination of tides and sea floor topography which is hidden in the position equations in their present form. The origin is defined by locating it such that the slant ranges from it to each of the three transponders are all equal. Any environmental change which would have a non-uniform effect on the transponder ranges could shift the origin, thus appearing to be a motion of the sea floor reference point. All points for which the three transponder ranges would be equal lie on a line perpendicular to the plane defined by the transponder triad. The origin is the point at which this line intersects the near surface horizontal plane on which the interrogate/receive transducer lies. If the transponder plane is tilted by an angle β and the depth to the array center is z at low tide and $z+h$ at high tide then the origin will move a horizontal distance βh. In the open sea h will rarely exceed 2 m. If the motion is to be kept in the 1 cm range then the transponders must be placed at such depths that β is less than 0.005 rad. In deep water (5 km) this means that, with units 6 km apart they should lie within 30 m of the same depth. In most deep sea areas it should be possible to live with this constraint. One way out, however, would be to change the depth of the (near surface)

interrogate/receive transducer to compensate for tidal motion. In this way one could reduce the vertical excursion by a factor of 10 and increase the allowable depth differences among the transponders to as much as 300 m, which would be a very simple requirement to meet

A second constraint on transponder depth arises from the fact that in 5 km water depth, a change of $2x10^{-6}$ rad in the direction of the perpendicular to the plane of the array leads to a shift of origin of a centimeter. If the units are separated by 6 km this implies an independent depth change for any particular transponder of just over a cm. It is thus clear that these units must be placed on competent rock or, if on softer material, they must be only slightly negatively buoyant, with large bearing area such that they will not settle into the sediment. The limited number of deep sea areas in which bottom currents are strong enough to scour around such an object would have to be avoided, or given special consideration to shield the unit such that scouring would not occur.

The reference hydrophone and the antennas must be mounted on some sort of floating structure, which inevitably will be moved about by the ocean's surface waves. If only one-way acoustic propagation could be used (as for the radio signals in the GPS part of the system) this would not be a problem, since signals arriving at or being sent from the reference hydrophone would relate to the instant of transmission or reception. In the transponder case the situation is more complicated because in a conventional system the reference hydrophone would transmit and the returns from the seafloor transponders would arrive at various subsequent times. Total travel times would be 5 to 10 seconds, during which substantial surface platform motion could occur. The time differences among the several paths can be as much as 1/10 second, during which time displacements of the order of a centimeter can take place during oscillatory motion at common wave periods (5-10 sec) with amplitudes of only 0.1 m. Since wave driven motions of conventional research ships or surface buoys can easily have amplitudes of over ten times that value it is clear that this requires serious attention.

An initial reaction is to try to avoid having such motion by selecting an appropriate vehicle on which to mount the system. FLIP, the manned spar buoy laboratory (Fisher and Spiess, 1963) penetrating 90 meters down into the sea, with resulting resistance to wave forces (Rudnick, 1967) could approach the desired situation, but would require an elaborate auxiliary measuring system to relate the location

of a reference hydrophone at its lower end to the antennae 100 m above with sufficient accuracy

The second reaction is to consider a more complex sea floor system in which the bottomed acoustic units would be the transmitters and receivers, with the transponder at the surface point being tracked Transmission times from the seafloor units would have to be arranged such that the signals all would arrive at the transponder within a hundredth of a second. The resulting travel times (or time differences) would be measured at the sea floor and telemetered to the sea surface. While this could be done, it is useful to look for still further (simpler) means.

The third approach is to recognize that the GPS receiving system on the vehicle must, in any event, be of an omni-directional type capable of producing multi-satellite outputs (available for subsequent averaging) corresponding to its location during any given hundredth of a second. The Macrometrics and Texas Instruments geodetic systems can do this now and the newest JPL version of SERIES may have the capability soon. With this in mind we can return to the simpler situation, with the transponders on the sea floor. Since it is desirable to measure the travel times for all units simultaneously (within about one hundreth of a second) we have devised a simple modification to do this

The precision transponders which we would use (Spiess et al., 1980 and Spiess 1979) operate in the following manner· A signal, coded to enhance travel time measurement, is sent from the vehicle to the transponder The transponder listens continuously, sampling and digitizing at a 1 Mhz rate the incoming sea noise and, when it arrives, the signal as well. The successive acoustic samples are loaded into a delay line exactly (within 1 μsec) 8 msec long which is updated as each new sample comes in, thus the most recent 8 msec of acoustic waveform is always in the delay line, maintaining a precise relationship to the incoming energy. When the recognition circuit determines that the signal to be timed has arrived, it shifts the delay line from receive to transmit and the stored signal goes back into the water with a time delay known to within 1μsec, even though the triggering of the recognition circuit may have a much larger uncertainty. For the present purpose we will add a small additional degree of sophistication to each transponder. Upon receipt of an acoustic command it will insert additional accurate 1 msec increments of delay into the re-transmission process. The user then sends out an interrogation pulse and observes the travel time differences for the several units. He then commands each one to use

an appropriate delay such that the several 3 msec timing signals will arrive in very close succession one after the other and makes a second interrogation. Presuming that the reference point has not moved substantially since the first, test interrogation, the several replies will in this instance all arrive closely enough spaced that no significant motion will occur during the succession of arrivals. With both the transmit and receive instants clearly defined, these can be matched with the corresponding GPS data points and the effective positions determined in spite of wave induced motions.

Although this relatively simple approach will essentially solve the wave motion problem it will still be desirable to use a vehicle which makes a good compromise between minimal response to the seaway and ease of relating the positions of the hydrophone and the GPS antenna(s).

As noted in section 2, if one operates near the origin in this system, the constraint on knowledge of sound speed is not difficult to meet in the open sea, however, this is only true if the sound speed is the same on all three transponder-reference hydrophone paths. A more accurate formulation of the problem starts with the range-travel time relationship:

$$C_i t_i = \left[(x_i - x)^2 + (y_i - y)^2 + z_i^2\right]^{1/2}$$

with $C_i = \frac{Co}{1+p_i}$, p_i being very small compared with 1. We put the origin at the common-range point defined by

$$r_o^2 = x_i^2 + y_i^2 + z_i^2 \text{ for } i = 1, 2 \text{ and } 3$$

and use i = 1 as the reference point with $y_1 = 0$ and $p_1 = 0$. Then, using $\frac{x}{r_o} \ll 1$, $\frac{y}{r_o} \ll 1$ and $p_i \ll 1$ we have, for the time differences $T_{1j} = t_i - t_j (j = 2, 3)$

$$\frac{CoT_{1j}}{r_o} = (1 - \frac{xx_1}{r_o^2}) - (1 - \frac{xx_j + yy_j}{r_o^2} + p_j)$$

Introducing the area of the sea floor triangle

$$A = (x_2 - x_1)y_3 - (x_3 - x_1)y_2$$

we find

$$\frac{x}{r_o} = \frac{(C_o T_{12} + p_2 r_o)y_3 - (C_o T_{13} + p_3 r_o)y_2}{A}$$

$$\frac{y}{r_o} = \frac{(C_o T_{13} + p_3 r_o)(x_2 - x_1) - (C_o T_{12} + p_2 ro_o)(x_3 - x_1)}{A}$$

The terms $\frac{p_j r_o}{C_o}$ thus appear as timing errors.

At this time we have no observational data from which to compute plausible open sea values of p_j Desaubies has recently published a paper [Desaubies 1983] which uses the Garrett-Munk [1975] internal wave model and gross vertical profiles of sound speed and water density to compute the expected variance of echo soundings in the deep ocean. For a 5,000 m deep station in the Sargasso Sea (about 30° N, 70° W), he calculates an rms fluctuation of just under 20 cm. This would correspond to an effective sound velocity variation of 4 parts in 10^5. The time scale of these fluctuations, however, is such that this number is more closely representative of the variability of C_o and falls comfortably within the tolerable limits on this quantity as discussed in section 2 He also treats the phase fluctuations or wavefront distortion which would be relevant to the extreme case in which the sea floor reference units would be very close to one another compared with the water depth. While his model in this case leads to a horizontal displacement rms error of 50 cm independent of water depth, he quotes experimental observations by Porter et al. using an operating frequency of 12 kHz as showing a phase variance smaller by 10^4 than Desaubie's theoretical values. He notes that their numbers are based on short duration samples (seconds) while his results would be relevant on a much longer time scale. They thus merely reinforce the conclusion presented earlier in this paper that a very short baseline system is not practical in this context.

Since one would expect the highest variability in the upper part of the water column we have looked at some data collected by Pinkel using a triplet of temperature and salinity sensors rapidly lowered and raised with horizontal spacing of about 40 m. from the stable manned spar buoy FLIP. At an open Pacific Ocean site at 31° 30′N, 122° 30′W, his data show a change of sound velocity computed over the depth interval from 95 to 400 m. of 0.19 m/sec (1.3 parts in 10^4) over a period of 20 minutes The difference between the effective sound speeds at separate sensors on simultaneous lowerings was below the limit of his measurement capability (at 2 parts in 10^5)

The principal conclusion from these fragmentary and not directly relevant observations is that this is the primary environmental factor which has not been investigated adequately to determine the extent to which it will limit performance of this system The ocean has enough areas of high spatial

variability (fronts of various kinds, breaking internal waves and "wakes" of islands or very large seamounts as strong currents flow past them) that this approach cannot be expected to perform well everywhere. On the other hand very large and relevant ocean areas are reasonably uniform and such results as those of Porter et al [1973] imply that values of p_j may lie in the range of 10^{-5} to 10^{-6}. We will return to this topic in section 5, below.

If the values of p_j are such that the effective timing error is greater than the 10 μsec dictated by the hardware as discussed in section 2 then the relationship between array size and accuracy of position determination will be different since r_o appears differently in the error term. While the position uncertainty decreases uniformly as the array area increases when the timing error is independent of range, the position error arising from inequality of sound velocity on the several legs is proportional to $(R^2+Z_o^2/R)$, which is a minimum when the horizontal radius (R) of the array is equal to the water depth (z_o). At this minimum,

$$E_x = E_y = \frac{2\sqrt{2}}{3} z_o E_p$$

where E_p is the error in p, which would usually be equal to p itself in any practical system. For the case of 5 km water depth this implies that p must lie between 2 x 10^{-5} and 2 x 10^{-6} for the position error to lie between 1 and 10 cm.

4. System Design

The complete system required to make geodetic measurements tying sea floor points to other reference points on land or sea over distances of tens of kilometers or more is composed of three parts: a GPS component to make the long range portion of the tie, a local platform subsystem to relate the GPS antenna positions to the acoustic reference hydrophone, and the underwater acoustic component which relates the reference hydrophone on the vehicle to the fixed sea floor coordinates In this study our primary concern is with the underwater portion, and the other two elements will only be discussed briefly

The particular GPS interferometer configurations which can be integrated into this overall system must be such that discrete outputs can be obtained which can be referred to particular instants in time within a few milliseconds. This implies an omni-directional antenna and either a multiple receiver sys-

tem (as in the Macrometer) or a fast cycling single receiver (as in the Texas Instruments geodetic unit). The individual observations occurring at the times of acoustic transponder transmission and reception would then be matched with the corresponding acoustically determined positions and the two sets of many points would be matched on a least square basis to provide the equivalent of the fixed station averaging essential to achieving sub-decimeter accuracy.

Since the GPS antenna(s) and the reference hydrophone must necessarily be separated by an appreciable distance it is essential that some method be used to relate them to one another. The details of the approach to this problem will depend on the nature of the platform from which the observations are made. One alternative to be considered would be the use of multiple GPS receiving systems whose antennas would be placed at widely spaced positions on the platform. A second alternative would be to use a gyro-based vertical and azimuthal reference system. For a modest-sized simple, rigid barge-like vehicle the vertical spacing could be as little as 10 meters and the necessary gyro system would probably be substantially less costly then multiple GPS. For larger vehicles (conventional ships or FLIP as referred to in Section 3) additional instrumentation would be required to compensate for possible flexure in the structure between the acoustic and GPS reference points.

Design of the acoustic portion of the system centers on two primary aspects: transponder power requirements and timing accuracy. Since timing error depends on received signal to noise ratio these two factors are linked. An additional source of timing error, however, is the uncertainty in the relationship between the time of arrival of the signal at the transponder and the instant of transmission of the reply. Units used in conventional systems today operate in the 7 to 16 kHz regime, receiving a signal at one frequency and replying at another. Pulses are simple sinusoidal wave trains 3 to 10 msec long depending on received signal level or signal to noise ratio. This is clearly not acceptable since it implies uncertainty of over a meter.

Our approach to this problem is to use the transponder strictly as a repeater, inserting a time delay controlled to the nearest 1 μsec. This is described in some detail in other publications (Spiess et al, 1980, Spiess, 1979). In this we digitize the hard clipped version of the incoming signal at a 1 MHz rate and load it, sample by sample, into a shift register which acts as a delay line This buffer storage

holds the most recent 8 msec of acoustic signal or noise being received at the transponder When a valid signal is recognized the shift register is disconnected from its input and its contents are transmitted back into the ocean, always with a time delay equal to the length of the delay line A unit of the type has recently been tested at short range (10-15m) under controlled but realistic conditions and yielded rms accuracy of 2 mm at 20 db signal to noise ratio using a 3 msec long pseudo random noise sequence with 4 kHz bandwidth

As discussed in Section 3 it is essential, because of anticipated wave-driven motion of the surface platform, that the transmit and receive instants at the hydrophone be nearly simultaneous for all three transponder paths. In order to achieve this we will simply add to each transponder a capability of receiving an acoustic command which will add 5 μsec increments to the delay time The system operator can thus control the overall time delay and arrange to have signals arrive from the several transponders in close succession

The problem of travel time estimation as related to such parameters as bandwidth, pulse length and signal to noise ratio has been treated extensively in the radar literature. For a coherent processing system in which a stored replica of the transmitted signal is cross-correlated with the received signal plus additive noise the generally accepted estimate of the best achievable rms timing errors, e_t is

$$e_t = \frac{1}{2\pi B\sqrt{2\frac{E}{No}}}$$

where E is the total signal energy received on any one path (E = ST where S is the average signal power and T the duration), No is the spectrum level of the background noise (total noise divided by bandwidth) and B is an effective bandwidth defined by

$$B^2 = \frac{\int_{-\infty}^{\infty} f^2 |\phi(f)|^2 df}{\int_{-\infty}^{\infty} |\phi(f)|^2 df}$$

where $\phi(f)$ is the frequency response function of the filter used to define the band. For a rectangular band of width Δf, $2B = \frac{\Delta f}{\sqrt{3}}$ (Carpentier, 1968)

Based on the above, using a band equal to one fourth the center frequency, a pseudonoise pulse length of 3 msec, sea state 3 background noise, transmit and receive directivity indices of 6 db and a range of 7 km the optimum frequency is between 10 and 15 kHz, with a requirement for about 20 milliwatt-seconds acoustic energy per pulse. Assuming a conservative 25% efficiency for conversion from electrical to acoustic energy gives a requirement for 0 08 watt-sec. per transmission, or 45,000 pulses per watt hour of battery energy. We are thus within a reasonable working range if we anticipate between 10^3 and 10^4 interrogations per visit, without having to provide battery replacement at too frequent intervals.

Site selection and transponder installation will play a major role in the successful application of this technique. Primary use of this approach would be in observation of crust distortion on scales of tens of kilometers or larger. This implies some latitude in selection of specific transponder locations. Existing systems such as Deep Tow and Seabeam are available to provide site selection data. As discussed in Section 3, areas of low relief should be preferred, with transponders placed at broad topographic lows to avoid possibilities of local sediment slumping contaminating the measurements. In most such situations rock outcrops will not be easily available as installation points. Detailed design of a transponder mounting configuration and launching procedure will be treated in a subsequent report; however, the general form would include a long (e g. 10 m.) pipe driven into the bottom by gravity (as in a sediment coring operation), with a broad horizontal plate at the sediment surface to prevent the unit from settling into the sediment after initial installation.

Once the transponders have been installed there should be a local survey to determine the internal geometry of the array. Based on prior studies (Spiess, in press) these should achieve centimeter level accuracies and, in conjunction with precise sound velocity measurement techniques under development in this contract, should provide the quantities needed to calculate the desired near surface reference hydrophone positions.

5 Acoustic System Validation

Since implementation of the GPS portion of this system will be a relatively expensive effort it seems appropriate to visualize some means by which the acoustic portion of the system can be validated

independently. This can be done in a reasonably direct manner by installing a minimum of one additional transponder to provide redundancy and with it a measure of internal consistency. By placing four transponders in a very nearly square array it will be possible to be simultaneously in the near-center approximation for any subset of three. In that case there should be a consistent relationship between points determined relative to each of the four subsets and the residuals from the process of fitting the four coordinate systems relative to one another would be indications of limits on accuracy at that particular site due to inequality of sound speed on the several legs and on ability to define the geometry of the array

An experiment of this kind in two sites off the California coast would be the most logical next step in this program. The first would be in one of the basins of the borderland area (e.g. San Nicolas Basin) where one could begin a program to observe the deformation of this small continental element of the Pacific plate. A location of this sort, in 2,000 m. water depth and convenient to our San Diego base would be logistically simple and would provide an opportunity to debug the system. It is also in an area in which support for transponder launch and retrieval could be obtained from the Navy's submersibles (Sea Cliff and Turtle) based in San Diego.

The second site should be in deep water off the Southern California coast and would allow validation of a site which would be relevant to defining the rate of strain buildup across the San Andreas fault zone out to the truly oceanic portion of the Pacific plate, again maintaining a reasonable logistic situation.

Preliminary to initiating either of these campaigns, however, there are three smaller steps which should be taken. A prototype operational transponder, to act as a model for production of the several which will be needed for any comprehensive at-sea test, should be designed, built and tested It should be configured properly for installation in a typical oceanic sea floor/sediment environment Second, a preliminary sound velocity survey should be made using the techniques being developed under our current NASA support. Third, the detailed computational algorithms to support the data reduction from such a test should be developed. These three could be carried out in any sequence, or in parallel depending on the availability of funds.

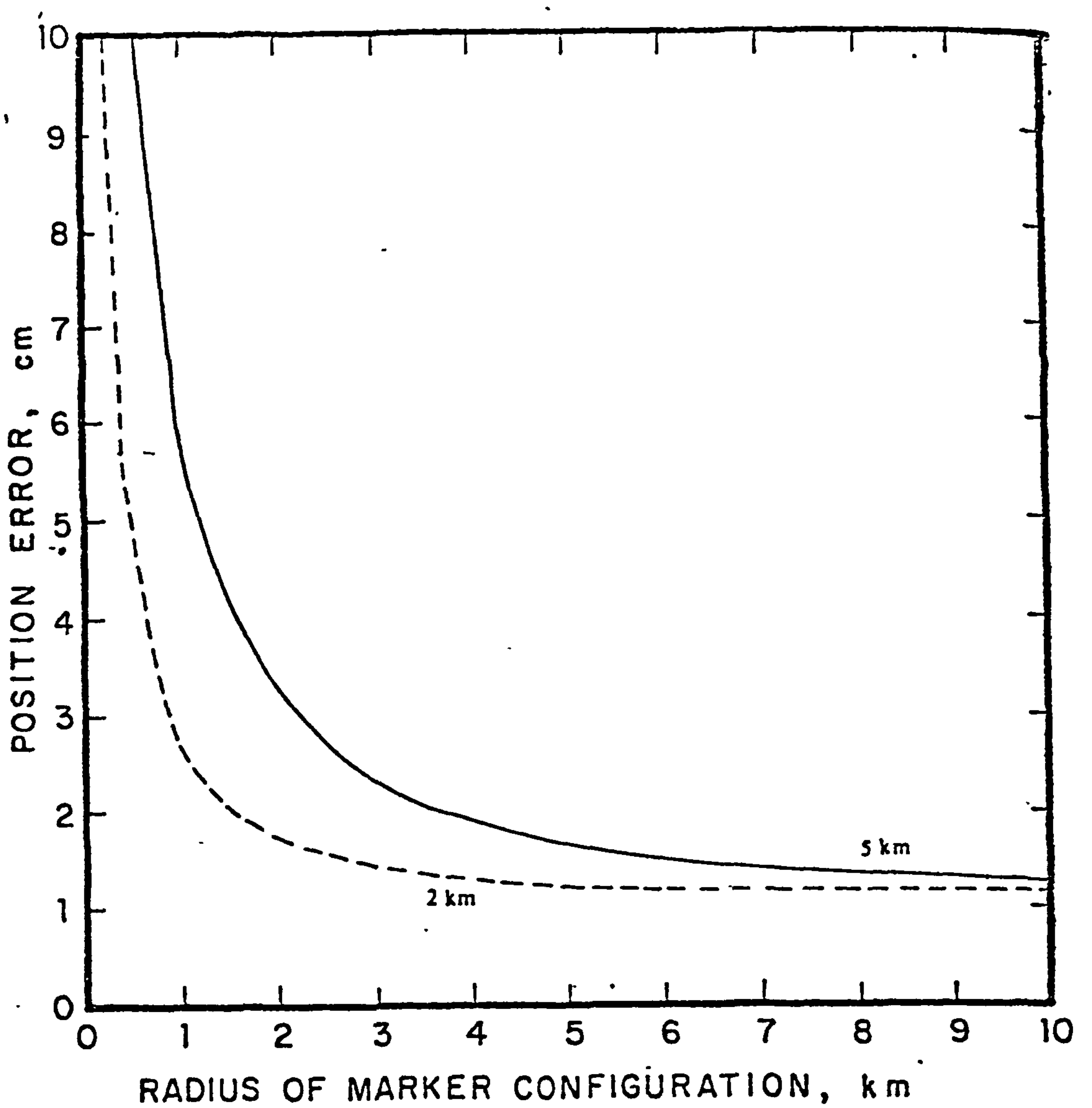

Figure 1. Error of a single position measurement (x or y) resulting from a timing error of 10 microsec. for a range of sea floor array radii in water depths of 2 and 5 km.